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Tunable ultraviolet and far infrared lasers for plasma diagnostics

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Abstract : Generation of tunable laser radiation is considered in the ultraviolet for thermonuclear fusion research and in the far infrared for plasma diagnostics. Both categories of laser radiation is generated by nonlinear interaction of laser radiation in a suitable material medium using Nd : YAG laser as the primary source. For the ultraviolet sum-frequency mixing is employed in Barium Borate crystal while for the far infrared self-beating of dye laser radiation is used.

Keywords : Tunable laser, non-linear materials, parametric devices, frequency conversion.

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1. Introduction

Lasers play an important role in plasma physics. These include generation, confinement, diagnostics, thermonuclear fusion and so on. Generation by existing high power high energy Nd : Glass and CO_2 lasers is being pursued in numerous laboratories all over the world. Characterisation of the generated plasma is routinely carried out by microwave radiation and far infrared lasers. However, lasers most suitable for excitation and absorption of energy by the generated plasma and conducive to realise Lawson criterion should operate in the wavelength range 250-400 nm [1]. The development of strong coherent source in the UV is also important for application in photochemistry and photobiology. But there are few lasers as such, in the ultraviolet and in the far infrared as required for purposes of plasma diagnostics and controlled thermonuclear fusion research. Out of the few methods available for generation of laser radiation in such wavelength range the techniques of nonlinear optics [2] is attractive and is potentially capable of providing large efficiency and wide tuning range. These are described in Sections 2 and 3.

2. Generation of tunable ultraviolet radiation

There are few primary lasers as such in the UV range. It is only through frequency-mixing techniques such as, harmonic generation and sum-frequency mixing of primary lasers in the visible and near infrared in appropriate non-linear crystals such radiations are generated. The crystals of importance are : Barium borate (BBO), Lithium triborate (LBO), Potassium titanyl phosphate (KTP), Urea and Potassium niobate. Table 1 illustrates some relevant properties of the crystals as compared to the familiar KDP crystal. Each crystal is associated with some advantages and disadvantages. The desirable properties are : wide possible transmission range, high laser damage threshold, adequate birefringence to allow efficient interaction and low susceptibility to temperature sensitivity. However, a small temperature

Table 1. Useful properties of some important nonlinear crystals.

Crystal	Transmission range (nm)	Relative nonlinear figure of merit	Damage threshold (GW / cm^2)	T (°C-cm)
KDP	200 - 1200	1	0.20	7.0
$LiNbO_3$	400 - 5000	23	0.05	0.6
$LiIO_3$	300 - 5500	40	0.50	50.0
BBO	190 - 3500	26	10.00	37.0
Urea	210 - 1400	10	1.50	
LBO	165 - 3200	7	6.00	4.2
KTP	350 - 4500	215	1.00	25.0
$KNbO_3$	400 - 5500	270	0.35	0.3

width would allow in addition to angular tunability temperature tuning in non-linear devices. Out of these BBO is near to idealism and that is why it has been the subject matter of various investigation. And various nonlinear devices have already been successfully demonstrated [3-5].

Table 2. Generation of UV-Visible-NIR radiation by some nonlinear techniques.

Sl No	Crystal	Interaction	Input / s laser (nm)	Generated wavelengths (nm)	Special feature efficiency (%)
1.	BBO	SHG	Dye	205 - 310	36.0
2.	BBO	OPO	308	354 - 2370	10.0
3.	BBO	OPO	360	406 - 3170	8.5
4.	BBO	SFG	Nd, Dye	217 - 291	4.0
5.	LiNbO3	OPO	1064	600 - 3700	
6.	LiNbO3	OPO	1060, 532	1300 - 4800	
7.	LiNbO3	DFG	Dyes	1500 - 4800	
8.	KTP	DFG	1064, Dye	1400 - 1600	
9.	KTP	OPO	1064	1800 - 2400	
10.	Uréa	OPO	1064	1800 - 2400	

Tunable ultraviolet, visible and near infrared radiation have been generated by harmonic generation of dye laser, by sum-frequency mixing of different primary lasers and by optical parametric oscillators pumped by different lasers. The latter include second and third harmonic of Nd laser, excimer laser, alexandrite lasers. Generation of longest infrared wavelength till its transmission limit 3.4 micron has also recently been reported by differencefrequency mixing [5]. Table 2 summarizes some of the demonstrated techniques for generation of tunable ultraviolet radiation in some nonlinear crystals. The shortest ultraviolet transmission of 160 nm is provided by LBO crystal. However, in BBO deep ultraviolet tuning 189 - 197 nm is obtained by sum-frequency mixing of excimer 248.5 nm with dye laser 788 to 950 nm [6]. By second harmonic generation of dye laser, the shortest obtainable tuning limit is 204 nm.

We have reported sum-frequency mixing of Nd laser and its harmonics with same pumped dye laser in BBO. The phase matched short wavelength tuning obtainable by sum-frequency mixing of second harmonic 532 nm and dye laser is 268 nm while that by third

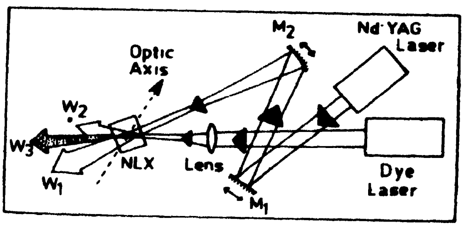

Figure 1. Schematic experimental set up for tunable ultraviolet generation by sum-frequency mixing. M_1 and M_2 are the dielectric coated mirrors and NLX stands for nonlinear crystal (BBO). W_1 and W_2 are the Nd : YAG and dye laser radiations while W_3 is the generated ultraviolet radiation

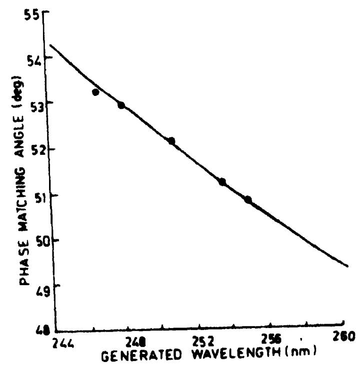

Figure 2. Angular tuning characteristics for generation of tunable ultraviolet in a BBO crystal using tunable dye laser radiation and 532 nm laser radiation as input sources The smooth curve is theoretically predicted while dots $\cdots\cdot$ represents the experimental points The experiment is done at a noncollinear angle $\alpha = 3.3°$

harmonic 355 nm and dye laser is 203 nm. Sum-frequency mixing with the fundamental 1064 nm and dye lasers provide shortest wavelength 360 nm. The experimental arrangement is shown in Figure 1. The major part of the Nd : YAG laser beam is used to pump dye laser while the remaining part directly or by harmonic generation in a DCDA crystal is combined with the generated dye laser beam in a 22.8° type I cut BBO crystal for sum-frequency mixing. With this crystal cut we have been able to tune as short as 246 nm in the ultraviolet end. The tuning characteristics is shown in the Figure 2. Using a noncollinear interaction the generation is made in crystal with near collinear interaction volume.

3. Generation of far infrared radiation

Nonlinear optical technique is attractive because it is potentially wide tunable in contrast to fixed frequency optically pumped lasers and raman lasers in the far infrared. Differencefrequency mixing in an appropriate nonlinear crystal excited by strong input pump lasers is capable of providing suitable FIR source. The input pump lasers may be dye laser, Ruby laser, Nd Glass laser or CO_2 laser [7-9]. Unlike the common nonlinear processes where all the three interacting frequencies lie within the crystals defined transmission range, only the two input laser wavelength lie here while the generated signal lie in the far infrared. As such crystal with good far infrared transmission is required. Various common nonlinear crystals have been proposed. Out of these $LiNbO_3$, $ZnGeP_2$, $AgGaS_2$ and $AgGaSe_2$ are important as regards availability and matching with pump lasers [10]. Experiments have been reported in $ZnGeP_2$ with CO_2 laser and also in $LiNbO_3$ with Ruby and Nd Glass lasers. We report self-beating of second harmonic of Nd : YAG laser radiation in $LiNbO_3$. Experimental arrangement is shown in Figure 3. Far infrared radiation is generated by beating of two modes within the laser oscillation line width. A polyethylene black sheet is used to block the unconverted green pump radiation from reaching the detector.

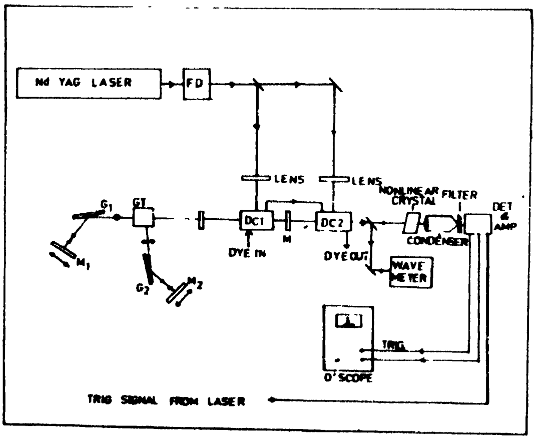

Figure 3. Experimental setup for submillimeter/FIR generation with dual frequency dye laser. M_1, M_2, M-mirrors. DC_1, DC_2-dye cells. GT-GLAN Thomson Prism. G_1, G_2-Gratings FD-Frequency Doubler.

The far infrared radiation is detected in a pyro-electric detector array followed by an amplifier. The nonlinear crystal is rotated and generation is obtained at an angle 9.4° to optic axis. The wavelength of the generated far infrared radiation is not measured but estimated (to be 800 - 900 micron) from the input pump wavelengths near its half-power points (0.53185 micron and 0.53220 micron). This is near the predicted crystal phase-matching angle as calculated from its refractive index data. To avoid uncertainty of the mixing wavelengths a dual frequency dye laser is designed capable of producing radiations at two clear wavelengths simultaneously. The cavity grating controls the dye laser wavelength which in turn determined generated far infrared wavelength. The dye laser was pumped by the second harmonic of Nd : YAG laser. The polarisations corresponding to the two wavelengths are made orthogonal by placing an intracavity Glan-Thomson polariser. The output of two dye laser wavelength are accurately measured with a wavemeter. Rhodamin 640 in methanol is used. With dye laser wavelengths at 0.6162 and 0.6157 micron far infrared output at 758.7 micron is generated. With one of the dye lasers changed from 0.6157 micron to 0.6155 micron keeping the other fixed at 0.6162 micron the generated output wavelength at 541.8 micron is observed.

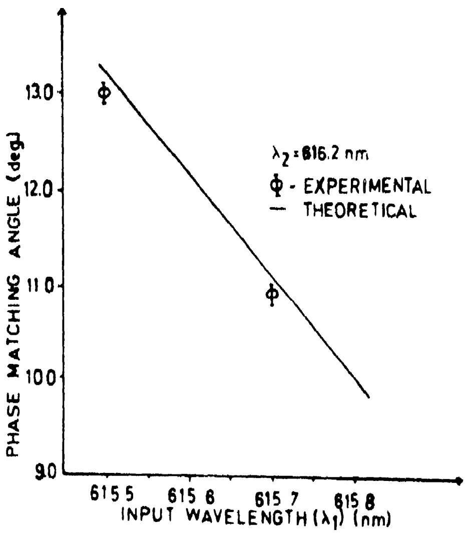

Figure 4(a). Variation of phase matching angle with input wavelength.

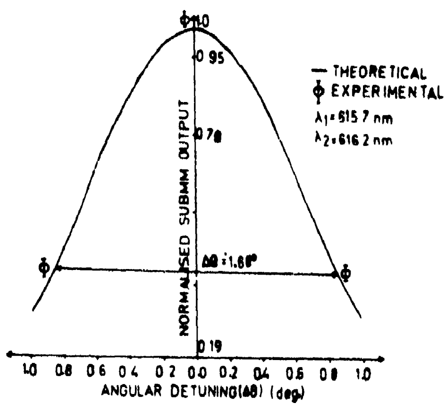

Figure 4(b). Normalized submm output vs angular detuning in both theoretical and experimental situations. θ_m Theoretical - 11.02 deg, experimental - 10 9 deg.

The theoretical tuning curve along with the two experimental points is shown in the Figure 4(a). Also shown in the Figure 4 (b) is the angular acceptance.

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